AFRL-VS-TR-1999-1508

Experimental Demonstration of Underground Structure Characterization Using Sensitive Magnetic Sensors

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29 Jan 1999

Scientific Report No. 1

AIR FORCE RESEARCH LABORATORY
Space Vehicles Directorate
29 Randolph Rd
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Hanscom AFB, MA 01731-3010

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REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY *(Leave blank)*	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	23 January 1999	Scientific Report No. 1

4. TITLE AND SUBTITLE
Experimental Demonstration of Underground Structure Characterization Using Sensitive Magnetic Sensors

5. FUNDING NUMBERS
PE: 63160D
PR: 4268
TA: SD
WU: AA

Contract No.: F19628-98-C-0015

6. AUTHOR(S)
Suman Ganguly

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Center for Remote Sensing, Inc.
11350 Random Hills Rd., Suite 710
Fairfax, VA 22030

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Air Force Research Laboratory/VSBI
29 Randolph Road
Hanscom AFB MA 01731-3010

Contract Manager: James Battis

10. SPONSORING/MONITORING AGENCY REPORT NUMBER
AFRL-VS-TR-1999-1508

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION AVAILABILITY STATEMENT
Approved for Public Release; Distribution Unlimited

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

The practical feasibility of detction and characterization of underground structures using electromagnetic sources in the ELF/VLF range is being investigated. For this, we investigate issues associated with sensors. One important objective is to examine the feasibility of using magnetic field measurements alone. We have developed unique 3-D e.m. models which can adequately cover arbitrary geometries, inhomogeneous ground, various excitation schemes and most importantly can handle a wide range of frequencies. We are currently performing numerical simulations using the 3-D e.m. code. We have established the need of 3-D modeling and there are no other codes which allow complete solutions for e.m. problems without any approximations. The results of these simulation will provide the experimental requirements.

It is impractical to measure E fields from a stand-off distance. We are pursuing simualtions to see if only the magnetic field measurement could provide the desired information. We have developed the most sensitive magnetic sensors which can be used from a remote location (such as from UAV). We plan to use these sensors for practical demonstration of magnetic-field-only measurements.

14. SUBJECT TERMS
E.M. modeling — ELF/VLF detection
Underground facility — Magnetic sensors

15. NUMBER OF PAGES
34

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	SAR

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1. INTRODUCTION

Deeply buried targets can be detected and characterized using the anomalies caused by void space, by their secondary effects or by the effects produced by materials within the target (see Table 1). Remote detection of associated activities and secondary effects may also be useful clues. Technical detection methods include: e.m. wave propagation, electric current flow, e.m. induction, magnetic field and gravitational anomalies, seismic wave propagation, heat flow, in situ probes, etc. (see table 2). Both active and passive techniques are used and the sensors could be deployed using airborne, surface and sub-surface techniques. (See Appendix A and B for detailed information about these techniques).

For broad area detection airborne and surface and/or subsurface techniques may be considered. Anomalies caused by gravity, heat flow etc. are generally too small to be used for remote sensing using satellite or high flying aircraft. Magnetic and electromagnetic field techniques show promise for airborne as well as for ground based deployment. For ground based deployment, concepts similar to internetted ground sensors may be used, where the deployment could be performed by dropping the sensors from UAV or other types of vehicles.

Magnetic and electromagnetic sensors can use both active and passive techniques. Sensing of the earth's magnetic field at different locations provides information about the magnetic anomaly created by magnetic and ferrous objects. Tunnel lining, concrete structure etc. contain strong ferrous objects which could be detected at distances/depths of more than 100 meters or so.

Various sources exist for low frequency anomaly detection. These include extreme low frequency fields produced by magnetospheric currents (magnetotelluric) covering the frequency range from almost d.c. to about 4-10 Hz. Lightning and other sources covering frequency bands of several kHz also exist. Notable amongst them are the VLF transmitters operating in the 10-25 kHz range and distributed throughout the world.

Controlled source electromagnetic sounding in the frequency range of 5 – 30 kHz has been used by geophysicists. The sources could be airborne or can be deployed at the ground surface. Sensors can also be either airborne or deployed in the ground.

TABLE 1
Status of Promising Sensors

Squid	10^{-10}G	Unchanged, No improvement expected.
Induction Coil	10^{-9}G	Unchanged, No improvement expected.
Fluxgate $5x10^{-8}$G		Improved sensitivity attained. Some improvements can be made.
Fiber Optic	10^{-7}G	NRL still trying to improve the sensitivity.
Piezo Magnetometer	10^{-7}G	Podney performing experiments. Hopes to achieve 10^{-8}G
Magnetostriction (Chip Mag)	10^{-6}G	Does not have much future.
Magneto-resistance	10^{-6}G	No immediate improvement
Micro Machined Tunnel Tip	10^{-6}G	Claiming to achieve up to 10^{-8}G. Doubtful.
Magneto-optical	10^{-8}G	?
Laser Pumped Devices	10^{-7}G 10^{-10}G	He^3 by T.I. has lowest d.c. noise. He^4 has l/f noise. Ce, Rb reduces gradient sensitivity

TABLE 2 **Fluxgate Magnetometer**	
Extremely low noise	$<5x10^{-8}$ G $Hz^{-1/2}$
High sensitivity	<25 mv/nT
Frequency range	d.c. to KHz
Extremely high dynamic range	> 120 dB
Extremely small, compact size	2 inch x 2 inch x 2 inch sensor
Very low power consumption	
Built-in electronics	
Digital output	
Fiber optic link (EMI proof)	
Interfaces to PC	

TABLE 3 **Remote Sensor Issues**	
Size	Sensitivity
Ruggedness	Sensor noise, stability, calibration
Stability (Acceleration, Temperature)	Lower/Upper frequency limits
Portability	Dynamic Range
Deployment schemes	Settling time
Configuration	Sampling rate

Underground deployment (using boreholes) of excitor and sensors is well known for geophysical exploration. They have generally been used for localized applications. The range of applications needs to be investigated using numerical simulation.

A unique man-made facility for generating variable frequencies covering a wise range e.g. from a few Hz to several kHz is being built in Alaska (HAARP). The major advantage of HAARP is its potential ability to vertically polarized signals covering a wide range in frequency. Since the propagation of ELF-VLF fields are associated with little attenuation, such fields may be used over large distances. The drawback is the small field magnitudes and the uncertainties of their generation and azimuthal polarization depending on ionospheric currents.

Other active sources may also be used for e.m. detection of tunnels. The source could be a loop at the surface of the earth, buried inside the earth or some portion of the earth itself. Whatever be the source of the e.m. field, adequate detection and characterization requires sensitive sensors covering a wide frequency range and other characteristics, independent of the mode of deployment. We propose to design and develop the most sensitive e.m. sensors based on some of the fluxgate and induction coil sensors developed by us. These sensors developed by the Center for Remote Sensing are the most sensitive in their classes. The fluxgate sensors have sensitivity of $5x10^{-8}G\ Hz^{-1/2}$ at 1 Hz and induction coils have sensitivity of about $10^{-9}GH^{-1/2}$ at 1 Hz. Currently, the fluxgate sensors developed through the DARPA program cover a frequency range of d.c. to 50 Hz, are compact (a few cubic inches) and low power. Further improvements are possible through incorporation of all digital electronics. Induction coil sensors currently provide frequency coverage of 1 mHz to 1 kHz.

The currently available induction coil sensors are bulky. The bulk arises because of the low frequency response of these sensors If the low frequency response is raised from mHz to several Hz, the bulk can be dramatically reduced. We propose to design and develop induction coil sensors where the lower frequency response is increased to about 100 Hz and the high frequency response could be extended to about 10 kHz. This modified induction coil sensor will be extremely compact and when used in conjunction with the fluxgate sensor, will provide almost continuous coverage from D.C. to 10 kHz.

They may also be used separately, depending on the depth of the target and the nature of the e.m. sources.

For any surface, the penetration of a periodically varying electric field perpendicular to the surface of the layer decreases exponentially away from the surface and can be expressed as

$$E_z = E_0 c^{-z/\delta} \qquad (1)$$

where E_0 is the electric field at the surface, z is the distance from the surface and δ is the skin depth of the material. The skin depth is given by the expression

$$\delta = \frac{c}{\sqrt{2\pi\mu\sigma\varpi}}$$

where c is the speed of light, ω is the angular frequency of the periodically varying field, and μ and σ are the permeability and conductivity of the material.

The choice of frequency is thus directly related to the depth of the target and for most practical purposes covers the frequency range of a few Hz to about 5 kHz. Although the lower frequencies offer larger depth of penetration, they offer poorer spatial resolution. Sophisticated array principles may be used for improved resolution and these require signal processing using improved sensors.

The general principles of using e.m. sensors are well established and reasonably straightforward. In a homogeneous background the electric and magnetic fields fall off monotonically with distance and the ratio between the electric and magnetic fields gives the impedance. The presence of inhomogeneity results in changes in effective impedance and altars electric and magnetic fields as well as their ratios. Measurement of the electric and magnetic fields and determination of the effective impedance is a rigorous approach for detecting buried targets. A tunnel (i.e., a void) will increase the effective impedance.

Measuring the electric field, however, is not easy. The ambient (probing field) field is predominantly vertical and the horizontal component is extremely small. Small deviations of the electric field sensor from horizontal position will result in large

deviations of the electric field sensor from horizontal position will result in large contamination by the vertical field. The question of how to position a horizontal electric field sensor over irregular terrain remains open. The usual approach is to use a long wire stretched over the ground and well grounded at both ends. This essentially uses the ground as the electric field probe. Intimate connection with the ground is difficult during covert operations, particularly when deployed from airborne vehicles. When airborne measurements are performed, the horizontal electric field may not be measured because of contamination due to the vertical field.

A second approach used in geophysics is to measure the tilt angle of the wavefront. It is well known that the finite conductivity of the ground results in tilted wavefront of a plane propagating wave and that the tilt angle is directly proportional to the effective impedance of the ground. The tilt angle may be measured using only magnetic sensors and is a practical way of measuring the impedance anomaly. A somewhat similar technique consists of measuring the horizontal and vertical gradients of the magnetic field in conjunction with the field itself.

Details of this approach are described in the Appendices. It remains to be seen if the magnetic field measurements alone can provide sufficient information about the anomalies.

One of the most significant issues is the stand off distance or range, from the target, where perceptible signal deviations caused by the tunnel are observable. This depends on the frequency, the size of the tunnel, the illumination field, its orientation and most importantly, on the ambient noise.

The ambient noise in the low frequency range is almost a monotonically decreasing function of increasing frequency. For the frequency range of d.c. to about 10 Hz, the noise is mostly of magnetosphere origin and has a large correlation length. Center for Remote Sensing has developed a scheme for cancellation of the ambient noise using multiple sensors (U.S. Patent 4,675,606; Magnetometers for Detecting Metallic Objects in Earth's Magnetic Field, S. Ganguly, 1987). Signal processing schemes have been perfected to recover extremely weak signatures in presence of strong ambient noise. Future detection of sensitive signals must utilize these improved signal-processing techniques.

Even with the best detection, the stand off distance probably is limited to something less than a wavelength of the probing field. This makes the broad area detection from a large stand-off-distance extremely difficult. Even with low flying craft such as UAV's, the platform stability becomes critical and special provisions must be made to stabilize the platform or at least have accurate measure of the platform orientation in 3 dimensions.

One approach is to obtain scalar values by measuring three orthogonal vector components, squaring and adding them. The scalar quantities are independent of platform orientation and can be used in detecting underground targets from reasonable stand off distances. The vector quantities, however, provide some direct information on impedance, which is lost when using the scalar quantities. The scalar quantities can be used for detecting discontinuities created by the presence of a target.

Presence of the ferrous materials inside a tunnel produces strong perturbations in earth's magnetic field. This can be viewed as remote sensing where the earth's field is used as an active source. This is a strong source and produces perceptible changes at large distances. Using the magnetic sensors developed at CRS, we have demonstrated (DARPA #DAAH01-95-C-R124) detection of a six foot long, 1" diameter disc, steel rod at a distance of 70 feet and detection of a hand grenade shell at a distance of about 3 feet. If the underground tunnel has at least six feet of steel rod (1" disc) in it, we can detect it at a depth of 70 feet. The magnetic detection falls off as $(\text{range})^{-3}$ and there must be 180 feet of steel rod if the detection range is to be increased to about 210 feet. Magnetic detection is an extremely useful technique for detecting the tunnel lining, concrete tunnels and the like. We propose to incorporate magnetic detection in the overall detection strategy.

Various electric and electromagnetic emissions are also associated with activities in the tunnel. These include 50 or 60 Hz emissions from power cords, generators and other machines, emissions from motors, generators, internal combustion engine, drilling machines, air circulators, refrigerators, etc. Leakage from communications system, radio, telephone, etc. One must concentrate mostly in the low frequency end of the spectrum, where the e.m. field must penetrate the ground above the tunnel.

CRS has performed measurements of field emissions from various automobiles and the low frequency ignition noise (spark firing) can be detected at ranges of up to a few hundred feet. We propose to incorporate these field measurements with the overall sensor development.

The composite sensor will have a frequency response of d.c. to tens of kHz. It will have the high sensitivity attainable using reasonable electronics without using liquid Helium. It must provide vector outputs of the magnetic fields which might be easily combined to provide scalar quantities and it must provide easy measurement of field gradients. Furthermore, the sensors should be compact, low cost, low power consumption and able to operate unattended over an extended period of time.

One of our objectives during this effort is to define state-of-the-art electromagnetic sensors which can be deployed under different circumstances and can be adapted for various types of active sources. For this we propose to design and develop extremely sensitive e.m. sensors covering the frequency range of d.c. to about 100 kHz. The major issues involve:

Sensitivity
Compactness
Power Consumption
Tri-axial Measurements
Gradiometer Applications
Insensitivity to Rotation and Vibration
Ambient Noise Cancellation
Ruggedness
Cost

We propose to address various issues and investigate their relevance to broad area detection of underground structures. We addressed these issues in relation to various sources of e.m. emissions, such as:

1) Earth's magnetic field and magnetospheric natural emissions for frequencies 0-10 Hz.
2) ELF-VLF emission from HAARP
3) VLF transmitters

4) ELF transmitter (Wisconsin Facility, Kola Peninsula)
5) Active sources in the ELF-VLF range using ground based, airborne loops as well as remote excitation of ground itself
6) Emissions from activities inside the tunnel

We considered the propagation of the e.m. sources and their interactions with the underground structures and consider both ground based and airborne deployment of the proposed sensors. Because of the diverse nature of tunnels and the surroundings, no single technique can provide unique signatures and the proposed approach of using a wide range of frequencies will provide the most useful detection and characterization strategy for most of the situations.

Predictions of the electric and magnetic field components caused by the tunnel or arising through activities inside the tunnel involve complex e.m. modeling in 3-D. During Phase I we have investigated the e.m. interactions and have developed unique 3-D modeling tools for generalized solution of related e.m. problems. The frequency range can be varied from d.c. to several MHz and arbitrary geometries, shapes and electrical characteristics can be modeled. We have developed the basic code and have performed some preliminary analysis using this 3-D code.

Based on these analysis, we provided detailed sensor requirements and sensor definition. We investigated the various e.m. sensor technologies and provided the design of the optimized e.m. sensor. The sensor package will also consist of the data acquisition and signal processing schemes.

2. REQUIREMENTS ANALYSIS

We have investigated various e.m. tools and techniques which could be applied for the geophysical problems. We were disappointed to find that there is currently no code available which allows accurate 3-D modeling of geophysical situations and covers a wide range of frequency.

Geophysicists are using 2-D codes or are using various static approximations. None of these appear suitable for the proposed task. 3-D codes have been developed at Sandia Laboratories, but they do not allow simulation to ELF/VLF bands. We have

started developing a unique code in collaboration with Prof. Raj Mittra of Penn State University.

2.1 Forward Modeling

Electromagnetic modeling of complex ground structures has been very limited. Most of the researchers used simple models like plats and spheres embedded in uniform and/or layered half-spaces (Palacky and West, 1991). In the last decades 2D and 3D modeling have been attempted using:

Integral Equations

Finite Element

Finite Difference

Parallel Implementation of Finite Difference Solutions

All of them suffered from some difficulty or other, when complex earth structures, arbitrary geometries, varying frequencies and different excitations were considered. Integral Equations showed some promise but suffered from the computational requirement of having to solve a full matrix system of the order of 3N. The computational solution time is generally dependent upon $(3N)^3$.

Thus IE solutions are only practical for compact bodies. In order to arrive at an efficient solution for the more general geometries, differential equation (DE) solutions to Maxwell's equations must be employed.

DE methods differ from IE methods in two important aspects: (1) the fields must be solved everywhere on a grid within and above the earth rather than just within the inhomogeneity and (2) the matrix system that is produced is sparse and diagonally banded. As the size of the problem increases, because the matrix is sparse, the solution of the unknown EM fields with DE schemes is much less time intensive than IE methods, especially when iterative Krylov subspace methods are employed (Ashby, Manteuffel and Saylor 1990). Thus, although the fields must be solved for everywhere, large, general models are much more manageable using this type of solution.

Newman and Alumbaugh (1995) from Sandia Labs developed a frequency domain model of airborne e.m. response using a staggered finite difference technique.

This is perhaps the most successful 3-D code. It, however, can not be used for ELF/VLF range, because of the computational time burden.

Geophysicists have used either a 2-D code or used various approximations. If $\sigma > \omega t$, then diffusion predominates, whereas $\sigma < \omega t$ they consider wave propagation. For ELF frequencies, they also neglect the displacement currents.

For realistic prediction of the electric and magnetic field distribution at and above the ground, a reliable, versatile, computationally efficient technique is needed. The requirements for the comprehensive code can be summarized as follows:

1) It should be able to model inhomogeneous ground and terrain. It would allow introduction of voids and anomalies of arbitrary geometries, and with arbitrarily complex materials.
2) The source of e.m. excitation can be placed anywhere: in the far field, in the ground (E and H field excitation) or above the ground.
3) The frequency of excitation can be varied from d.c. to hundreds of kHz.
4) The electric and magnetic fields should be predicted at any location (in, at or above the ground).

Development of such a code for solving the generalized forward problem is a formidable task.

Perhaps the most important difficulty in the development of a generalized e.m. code is covering a large frequency range and at the same time maintaining sufficient grid size resolution, in order to adequately model the cavity. Conventional Finite Time Domain Analysis fails for frequency range below about 1 kHz. An ingenious technique has been developed to solve the 3-D problem over the frequency range of almost d.c. to as high as hundreds of kHz.

2.2 Inverse Problem

Simulations using forward modeling are essential before undertaking the inverse problem. In general, the spatial measurements of the electric and magnetic field patterns at different frequencies can be used to reconstruct the underground structures. The inversion can be performed through tomographic techniques, through rapid relaxation algorithms, or by other A.I. based approaches.

We propose to perform numerical simulation of various underground structures at different depths and using different ground conductivities. We simulate various sources covering frequencies of d.c. to about 10 kHz. We analyze the field perturbations produced through tunnels and estimate the fields and their gradients at different stand off distances, at various heights from the ground and on the ground. We analyze these results and investigate the relationships of stand-off-distance, frequencies, tunnel size and depth, etc. on the horizontal resolution of sampling. From these analysis and relationships we determine:

1) The horizontal and vertical gradient in magnetic fields
2) Horizontal gradients and discontinuities
3) Extent of altitude from where measurements can be performed
4) Dept of the target and the range of frequencies.

These results and analysis will allow us to draw valuable inferences regarding the deployment scenarios as well as the requirements of sensors at different frequency bands. We specify the sensor requirements based on these investigations.

Results of these simulations will also allow us to develop the inversion algorithm. It is believed that measurements at different frequencies will contain the depth information, whereas the spatial (x,y,z) field components (E and H) will allow the determination of the effective impedance. The impedance profile of the underground facility could be derived using E and H measurements at different frequencies.

Measurement of E field, however, may not be practical from remote sensors. Attempts should be made to obtain sufficient information using the H field measurements alone (see Appendix B).

Inversion can also be performed using boundary or edge detection and by the use of inversion processes will be developed after exercising various simulations. Some simulations are shown in the next section.

3 CONCLUSION

A novel 3-D e.m. model has been developed. This technique allows modeling of the e.m. field components at any location, inside the ground, inside the tunnel, above the ground, etc. to be determined. The ground can be modeled in 3-D using inhomogeneous

material and any arbitrary shaped tunnel, cavity, void or anomaly can be modeled. The tunnel or cavity may be composed of void or can be filled with dielectric and conductive material (water, metal rods, pipes, electric cables, etc.).

Various e.m. sources can be used for excitation. The sources can be placed far away, resulting in propagating wave in the earth ionosphere waveguide above the region of interest. This situation is similar to what would be expected for HAARP or from other ELF/VLF sources. Otherwise, the e.m. sources can be located in nearby ground using magnetic field (magnetic loop) or electric field excitation (electric diapole). The sources can be placed above the ground or can be embedded in the ground. Sources may also be placed in the cavity itself (generators, power cables, etc. in the tunnel).

The frequency of excitation can be varied between d.c. to arbitrarily high frequencies (MHz). A special technique has been developed to extend the low frequency limit and still maintain computational accuracy. There is no other code in existence which allows such generalized treatment of the forward problem.

The simulations have established that the complex field interactions demand 3-D modeling and that 3-D results may not be extrapolated from using 2-D models or using simpler geometries. Results of the 3-D modeling are essential before solving the inverse problems.

The field perturbations in various components contain enough signatures of the underground structures to allow detection. The field perturbations of major components are easily detectable using sensitive sensors. Both plan wave and localized sources can be used for optimized detection depending on soil conditions, depth, tunnel geometry and orientation and most significantly on the sensor deployment scenario. The generalized e.m. code can be used for the optimization and for development of the inversion procedure.

Field measurements can be performed either at the ground level or using aerial vehicles. Borehole sensors may also be modeled and considered. The practical frequency range varies from a few Hz to hundreds of KHz. Various sources of excitation and method or sensor deployment can be used for optimized detection of various underground structures.

For low frequencies (that is, d.c. to kHz) magnetic field sensors are practical. There are basically two types of magnetic field sensors, magnetometers and induction coils. We have surveyed the complete range of technology and two types of magnetometers seem promising. One is the fluxgate magnetometer and the other is the Atomic Resonance magnetometer. These magnetometers offer magnetic field measurements from d.c. to tens of Hz. The frequency range for a specially designed fluxgate can be extended to tens of kHz. The design for such extension in frequency range has been performed.

Induction coils on the other hand provide measurements of dB/dt and offer the most sensitivity for frequencies above a few Hz. For low frequency operation (at tens of Hz) the induction coils are extremely bulky. An induction coil with high sensitivity (10^{-9} Gauss $Hz^{-1/2}$ at 1 Hz) typically has dimension of 1m x 10 cm x 10 cm and weighs about 15 pounds. If the low frequency limit is extended to say a few kHz, the size and weight become comparable to that of a fluxgate magnetometer.

The fluxgate magnetometer currently offers a sensitivity of about 5×10^{-8} G $Hz^{-1/2}$ at 1 Hz. They operate from d.c. to some tens of Hz. CRS has developed the most sensitive fluxgate magnetometers. These devices typically are contained with 2-inch cubes and weigh a few ounces. Current fluxgate devices use analogue electronics. Initial design and plans for extending the frequency range have been drawn. Further improvements are needed in terms of improving the electronics (using digital) and in improved core materials.

Orthogonality of these sensors (both fluxgate and induction coils) are also extremely important, particularly for UAV based applications. Vibration and rotational effects in the UAV based applications can be minimized using three orthogonal components and by forming the scalar value. Further improvements in orthogonality needs to be performed.

Atomic magnetometers give the scalar value of the magnetic field directly and may be extremely useful for UAV based applications. Currently they offer sensitivities of the order of 10^{-7} GH_z at 1 Hz. Further development of this technology offers strong promise of attaining sensitivities comparable to fluxgate magnetometers.

APPENDIX A:

Direct-current Measurements of Resistivity.

During the second decade of this century, at approximately the same time in France and in the United States, a standardized electrode array was used to make direct-current measurements of resistivity, and appropriate techniques for interpreting the field and deriving the resistivity for the earth from these measurement were proposed. Over the ensuing half-century, the direct-current sounding method, particularly one that uses the Schlumberger array, has become an effective and popular method for carrying out subsurface studies.

One such area, which has seen a considerable amount of development in recent years, is that of Electrical Well Logging, which attempts to determine the electrical properties of the rocks in the local area, and then interprets the results of geophysical surveys to determine the location of ores or oil deposits. The following measurement techniques are used for recording the electrical resistivity logs:

(i). Single-electrode resistance logs;
(ii). Multi-electrode spacing logs;
(iii). Focussed current logs;
(iv). Micro-spacing and pad device logs;
(v). Induction logs.

Galvanic Resistivity Methods

The galvanic resistivity methods are those in which current is driven through the ground using galvanic contacts.

Two pairs of electrodes are used to generate these logs. Current is driven through one pair of electrodes and the potential established in the earth by this current is measured with the second pair of electrodes.

The Schlumberger array is designed to measure the potential gradient in an approximate manner.

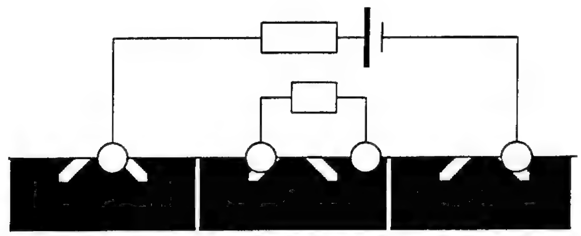

Fig. A-1. Resistive log measurement

The limitations of the direct current sounding methods are listed below:

(i). They work best in moderately conductive rocks, where the resistivity is to be determined, at most, to a depth of a few tens to a few hundred of meters.

(ii). The amount of effort involved in direct-current soundings becomes very large if one wishes to study the resistivity structures at large depths.

(iii). The results obtained with direct-current surveys are sometimes ambiguous, so that the desired exploration target cannot be recognized.

Magneto-Telluric Resistivity Method

To extend the capabilities of electrical prospecting methods, and to supplement the already existing direct-current sounding methods, the magnetotelluric method was developed.

In contrast to the direct current method, the magnetotelluric method makes use of the magnetic coupling that occurs between current filaments flowing in the ground when the current is not DC. This aspect of current behavior makes it possible for an electrical method to provide penetration through a very resistive zone, a case in which the direct-current method can provide no penetration. The magnetotelluric method has become a widely-used and effective method for studying the resistivity structure of the subsurface at depths ranging from a few hundred meters to depths of a few tens of kilometers and, in some exploration efforts, to depths as large as several hundred kilometers.

Electrical currents induced in rocks by fluctuations in the earth's magnetic field may be used to measure the resistivity. The time variations in the measured magnetic field arise from the magnetic component of a plane electromagnetic wave. A simple relationship can be shown to exist between the amplitude of the magnetic field changes, the voltage gradients induced in the earth, and its resistivity.

Also, since the depth to which an electromagnetic wave penetrates into a conductor depends both on the frequency of the probing field and on the resistivity of the conductor, the resistivity may be computed as a function of depth within the earth if the amplitudes of the magnetic and electric field changes can be measured at several frequencies.

Important advantages of the magneto-telluric method, over the galvanic methods, for measuring the resistivity are:

(i). In contrast to the galvanic method, there is no problem in determining the resistivity beneath a highly resistive bed, because the measurements are carried out with currents induced in the earth.

(ii). Resistivities may be measured down to great depths within the earth Measurements to similar depths using galvanic methods would require the use of very powerful sources.

One disadvantage of the magneto-telluric method is that it needs highly sensitive instrumentation to measure the amplitude of small, rapid changes in the magnetic field.

Apparent resistivity is derived by measuring the wave impedance over a uniform earth. Let us assume that we have a plane wave incident upon the interface between two media as shown in Fig.2 below.

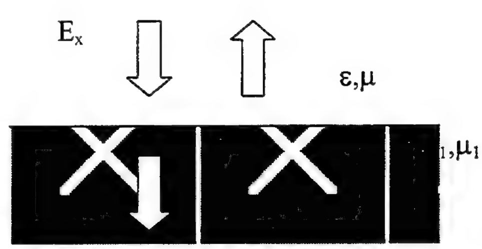

Fig. A-2. Plane wave incident upon two media.

Using the superscripts *i* and 1 for the incident and transmitted fields, respectively we can write:

$$E_x^{\,i} = E_0 e^{-jkz}$$
$$E_x = R\, e^{-jkz}$$
$$E_x^{\,1} = T\, e^{-jkz}$$

$$H_y^{\ i} = -\frac{1}{j\omega\mu}(-jk)E_0 e^{-jkz}$$

$$H_y = -\frac{1}{j\omega\mu}(jk)R\,e^{-jkz}$$

$$H_y^{\ 1} = -\frac{1}{j\omega\mu_1}(-jk_1)Te^{-jkz}$$

The boundary condition at the interface is given by

$$\left.\frac{E_x^{\ i} + E_x}{H_y^{\ i} + H_y}\right|_{z=0} = \left.\frac{E_x^{\ 1}}{H_y^{\ 1}}\right|_{z=0} = Z$$

We can express Z in terms of the medium parameters as

$$\left(\left.\frac{E_x^{\ i} + E_x}{H_y^{\ i} + H_y}\right|_{z=0}\right)^2 = \left(\left.\frac{E_x^{\ 1}}{H_y^{\ 1}}\right|_{z=0}\right)^2 = Z^2 = \frac{\mu_1}{\varepsilon_1} = \frac{\mu_1}{-j\dfrac{\sigma_1}{\omega}}$$

$$\frac{1}{\sigma_1} = \frac{1}{j\omega\mu_1}\left(\left.\frac{E_x^{\ 1}}{H_y^{\ 1}}\right|_{z=0}\right)^2$$

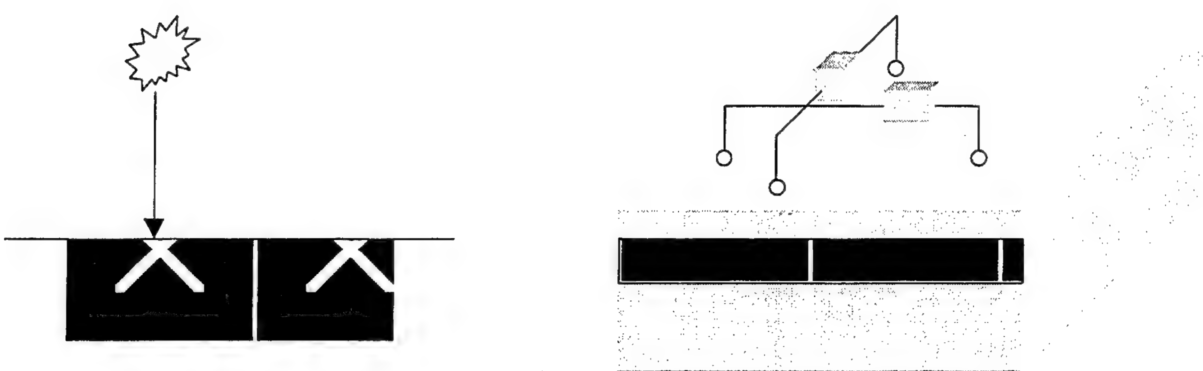

Fig. A-3. Impedance measurement setup

Telluric Current Methods

The magneto-telluric method for measuring the earth resistivity is a challenging problem, because it requires the detection of magnetic field variations with very small amplitudes.

In contrast to the above approach, the telluric method for studying the changes in earth resistivity utilizes the same natural magneto-telluric field for power, but only requires that the electric field components of the field be measured simultaneously at several locations. However, since the earth resistivity cannot be measured in absolute values, the telluric current method may be viewed as a special version of the more general magneto-telluric method.

Electromagnetic Methods

The primary limitation of the magneto-telluric method is that it requires the investment of substantial efforts in recording and analyzing the field data. Fluctuations in the magnetic field occur naturally and, consequently, the background noise level can be very high. The extraction of useful information in the presence of the noise is a difficult process and, as a result, the magnetotelluric method often does not provide the desired precision and accuracy. Another approach to studying the electrical properties of the subsurface is the electromagnetic induction method, which makes use of the magnetic coupling between current filaments in probing the earth. In addition, it utilizes a known and controlled source of energy, rather than depend on the use of random, naturally-occurring electromagnetic field.

Direct current and magneto-telluric methods are used much more frequently in the sounding of earth structures than are the electromagnetic methods, even though simple electromagnetic measurement techniques have been available for over five decades. This is perhaps attributable to the slow development of electromagnetic methods that require the use of advanced instruments and sophisticated knowledge of the underlying theory.

The principal application of electromagnetic methods has been in mining geophysics for the exploration of conductive ore bodies. For well over half a century, it has been recognized that certain types of ore bodies can be located by electromagnetic induction occurring in them. In order for the induction method to work, the ore body, which is

being sought, must have a relatively high conductivity in comparison to the host rock in which it occurs. However, not all useful minerals have this characteristic, and the principal ore minerals that can be explored with inductive methods are the sulfides -- both the base-metal and the uneconomic sulfides. Certain other minerals also have the property of good electrical conductivity, including the iron oxides, the native metals, and carbon in the form of graphite. Induction methods might be used for a wide variety of applications in which an underground structure is known to have a different electrical conductivity than the surrounding rock; but, primarily, we view the electromagnetic induction methods as being best suited for the exploration of relatively massive base-metal sulfide deposits.

Early electromagnetic soundings through a stratified earth appear to have been based on the "Eltran method" based on a patent by L. W. Blau (U.S. patent 1,911,137, issued in 1933). The Eltran method entails the generation of an electromagnetic field using a dipole excited by a current pulse, and the detection of the electromagnetic field with an electric dipole aligned with the source dipole. In concept, the energy reflected from the boundaries between layers with different conductivities can be detected in the recorded transient signal at the receiver in much the same way that acoustic reflections are detected when the seismic reflection techniques are used. The method aroused considerable interest among oil companies for about ten years. However, it became apparent later that, for highly conductive rocks normally found in sedimentary basins, the transient response to the impulse excitation contains frequencies that are so low that it would be difficult indeed to obtain the resolution needed to identify the individual reflected events.

All of the theoretical developments, both in the USA and in the former Soviet Union, have largely been for the case of a harmonic source of excitation. The assumption of a harmonic source allows certain simplifications on the formulation of the problem, but limits the applicability of the solutions to steady state conditions. In practice, measurements are made both in the frequency domain and in the time domain. In the frequency domain, the coupling between the transmitter and receiver is measured at a sequence of discrete frequencies. In contrast, a time domain measurement is considered to be one in which a waveform that is rich in its frequency content is used to energize the source, and only a single transmission need be used.

Frequency domain methods have been used quite extensively in profiling and in simpler applications, using a limited number of frequencies. However, much of the electromagnetic sounding work has been carried out by using one or more variants of the time domain method. A significant extension of the time-domain electromagnetic method was made when it was realized in the mid 1960s that the soundings could be carried out by using a source-receiver separation that is considerably less than the depth to be explored. Such a method has been called by various names, ranging from "short-offset" to "late-time" and "near-zone."

In mining exploration efforts, the use of the time-domain method, with little or no separation between the transmitter and the receiver, dates back a quarter of a century or more. The use of small separation in the time-domain electromagnetic sounding represented a significant advance in the technique, and was made possible by advances in theory. In frequency domain measurements, it is necessary to use a separation distance between the transmitter and the receiver that is several times larger than the depth to be investigated, unless some means for canceling the primary field is available (Kaufman, 1979). In time domain methods, the separation of the primary field from the measured field is rendered easily, because the two separate in time.

For electromagnetic sounding, the time domain methods appear to have significant advantages over the frequency domain schemes. The primary feature of the time domain method is that the transmitted waveform contains a broad spectrum of frequencies, so that a wide range of penetrations can be obtained simultaneously.

The theory underlying the electromagnetic methods is based on an analysis of the relationships that exist between the fields that are measured during a survey and the properties of the geoelectric section being explored.

(i) To interpret the measurements made by electromagnetic sounding it is necessary to develop modeling and simulation tools that can calculate

(ii) The primary electromagnetic fields produced by various types of sources, as for example, by current carrying loops of circular or rectangular geometry, as well as by electric dipoles located above the earth.

(iii) Electromagnetic fields in both the frequency and time domains, generated by currents in various types of confined conductors surrounded by an insulating host medium.

(iv) The behavior of the field at low, intermediate, and high frequencies in the frequency domain, or during the early, intermediate and late stages of transient response in the time domain. This understanding is helpful in determining the ranges of frequencies and times, and the parameters characterizing the conductive bodies, such as the dimensions, conductivity, precise location, and orientation of the primary source. Such an understanding enables us to specify an optimal range of frequencies or times within which the best relationship between the parameters of the conductor and the behavior of the field will be observed.

(v) Analysis of frequency and transient responses caused by currents induced in the medium surrounding an ore body. The geologic noise inhibits the purpose of a survey in finding an ore body and which ultimately will limit the maximum depth of investigation which can be achieved.

(vi) A quantitative description of the relationship between the location of a conductive body, its orientation, and its geometric form on one hand, and the characteristic features of the profiles for the various components of the electromagnetic field over that body on the other.

Conclusions

Techniques for geophysical prospecting were primarily developed to analyze the electromagnetic properties — such as the permittivity and resistivity of the earth — under the assumption that one is dealing with a layered dielectric structure, with the objective of locating ore bodies in rocks. The powerful arsenal of techniques based on the Direct Current (DC), Magneto-Telluric Current (MTC), Telluric Current (TC), and Electromagnetic Induction (EI) methods allow one to solve a great variety of problems in geophysical sounding and mining prospecting. However, the present problem of locating cavity-type voids in a layered dielectric medium has a different character than the problem focused on in the development of geophysical techniques. The medium in which the cavity is located, can be highly conductive and this fact makes it impossible to apply

techniques that are based on DC measurements. This is because the DC sounding methods work in moderately conductive rocks and, even under the unrealistic assumption that cavity is located close to the surface of the earth, the direct current explorations can be ambiguous and unreliable. While the MTC and TC methods solve the cavity location problem, the use of a random and natural electromagnetic field makes it very difficult to the process and extract useful information from the recorded field data. This is because the process of extracting the information can take a very long period of time due to the presence of high levels of electromagnetic noise.

This leads us to the conclusion that the technique for solving the problem under consideration should be based on the EI method. Since the layered medium surrounding the cavity is characterized by high losses, the penetration of electromagnetic waves deeply inside the structure can only occur at low frequencies; hence, the chosen technique must be accurate in the low frequency band. This requirement makes the direct application of various numerical schemes, such as the Finite Difference (FD), Finite Element (FE) and the Finite Difference Time Domain (FDTD) methods very inefficient, if not virtually impossible, to apply when the frequency goes below about 1 kHz. In light of this, we have proposed a new hybrid approach that combines the numerical methods, with asymptotic extrapolation and Fast Fourier Transform techniques, to derive the solution to the buried cavity problem.

Because of the inherent complexity involved in the 3-D modeling, one might be tempted to simplify it by considering the corresponding two-dimensional problem. This may be done by assuming that the buried cavity structure has dimensions that are large in the longitudinal direction, as compared to the dimensions of its transverse cross-section. However, the two-dimensional analysis is unable to predict the truncation effects in the longitudinal direction introduced by the ends of the cavity.

APPENDIX B:

Magnetotelluric Techniques and Magnetic Field Alone Based Reconstruction

1. Introduction

Magnetotelluric techniques rely on a plane wave launched from a distance source (typically earth's ionosphere/magnetoshpere). Such a "plane wave" was postulated in the Tikhonov-Cagniard magnetotelluric (MT) formulation that utilized the spectral impedance concept. In MT methods the spectral impedance input required by the inversion algorithms is computed using horizontal electric and magnetic field measurements. Measurements of electric field are cumbersome, requiring long wires and good contact with the ground. They cannot be performed using low flying airborne platforms.

Within the Tikhonov-Cagniard MT formulation equivalent spectral impedance values can also be determined using exclusively magnetic measurements. In this case sensitive horizontal or vertical magnetic gradiometers will be needed. We are investigating the issues associated with remote detection of underground objects using:

a) Electric and Magnetic filed measurements
b) Magnetic field measurements only

We are performing numerical simulation using the general purpose 3-D code developed by us. Based on these analyses we shall propose inversion techniques based on conventional impedance reconstruction or by using other techniques.

A principal impediment in the utilization of low frequencies for underground exploration is the lack of well characterized coherent, low-frequency "plane wave" sources that are capable of generating a wide spectrum of frequencies in a highly controlled manner. Nevertheless, in the absence of such low-frequency transmitters, geophysicists have over the years managed to exploit naturally occurring *random* sources of low-frequencies electromagnetic signals to perform valuable underground exploration. This exploration techniques is known as the magnetotelluric method[1] and is based on low frequency electromagnetic noise generated by random lightning impulses in the 10Hz to

few kHz range, and by natural currents flowing in the ionized upper atmosphere in the frequency range below.1Hz. Magnetotelluric results, despite their reliance on random sources, demonstrate the potential of low frequencies for mapping underground structures. Furthermore, the results clearly indicate that dramatic processing gain can be achieved if controlled sources "plane wave" were available, such as controlled broad band spectral sources or, preferable, time-extended coherent sources that span many decades in frequency.

In addition to their great penetration depth, low frequencies have the advantage of low attenuation and guided propagation over the ground, resulting in a broad coverage range from a single facility. The great propagation range of the low-frequency wave, heavily leveraged in the magnetotelluric investigations, has been confirmed in communication applications involving deeply submerged submarines. A single facility ocated in Wisconsin and operated in the 70 Hz range provides an extremely wide coverage range.

The lack of coherent, low-frequency, ground-based transmitters prevents the magnetotelluric techniques from reaching their enormous exploration potential. The difficulties in the construction of efficient low-frequency transmitters, which stems from their large free-space wavelength of several thousand kilometers, were clearly manifested in the construction of the U.S. Navy's Wisconsin transmitter. If large bandwidth is also required, these practical difficulties become insurmountable.

Another source of excitation is currently being considered by the Russian scientists. The facility at Kola Peninsula has about 100m of cable which can be excited by variable frequency (ELF/VLF) sources. The Kola facility may be used by U.S.A. scientists.

The development of a new type of source, denoted here as ionospheric sources (IS), opened a new era in imaging underground structures. Such sources are produced by modulating naturally flowing ionospheric currents using amplitude or frequency modulated powerful HF (3010 MHz) transmitters. A virtual low frequency antenna is generated in the ionosphere that radiates electromagnetic waves with a frequency equal to the frequency of the modulation. Varying the source modulation rate provides *continuous tunablility* across the entire low-frequency band between .001 Hz and 30 kHz.

2. Background

2.1 The Magnetotelluric Method

Traditional magnetotelluric (MT) methods are based on the Tikhonov-Cagniard model[9]. In this model it is assumed that the primary field which induces currents and secondary fields in the ground is a uniform plane wave, whose fields do not depend on the horizontal or vertical coordinates (Fig. 1). Such a field can be ideally produced by an "infinitely" large horizontal sheet at any height above the earth. For a horizontally stratified medium (Fig. 2) the currents induced into it are horizontal and serve as sources for the secondary fields. If, for simplicity, we consider a uniform half space (Fig.1) with conductivity σ it is easy to show (Vozott, 1989) that at the surface ($z = 0$),

$$E_x\,(z = 0) = |Z|\,H_y\,(z = 0)\,\sin\,(\omega\,t - \pi/4) \tag{1}$$

$$|Z| = (\omega\,\mu\,/\,\sigma)^{1/2} \tag{2}$$

Namely measurements of $E_x(z = 0)$ and $H_y(z = 0)$ can give the conductivity σ of the half space. It is customary to define an apparent resistivity ρ_a as

$$\rho_a = |Z|^2\,/\,\omega\,\mu \tag{3}$$

For a uniform half-space, if we measure the complex impedance.

$$Z = E_x\,(0)\,/\,H_y\,(0) \tag{4}$$

as a function of frequency the plot of $\partial\rho_a$ vs. ∂ will be independent of frequency, and its phase ϕ relative to the phase of $H_y(0)$, $\phi = -\pi/4$. The presence of any conductivity anomaly inside the uniform half space, will appear as deviation from the above rules, and can be imaged using standard inversion algorithms (Madden and Mackie, 1989).

The above results can be generalized to the case of n-layers with resistivity ρ_n and vertical extent h_n. In this case the impedance Z_n will be given by

$$Z_n = Z_1 R_n \tag{5}$$

and the apparent resistivity ρ_T by

$$\rho_T = \rho_1 \, |Z_n|^2 / |Z_1|^2 \tag{6}$$

In eqs. (5) and (6) Z_1, ρ_1 refer to the first layer and R_n is defined by

$$R_n = \coth\left\langle -ik_1h_1 + \coth^{-1}\left\{\sqrt{\frac{\rho_2}{\rho_1}}\coth\left[k_2h_2 + \coth^{-1}\left(\sqrt{\frac{\rho_2}{\rho_1}}\coth(-ik_3h_3 + \downarrow\downarrow + \left(\left(\sqrt{\frac{\rho_{n-1}}{\rho_{n-2}}}\coth(-ik_{n-1}h_{n-1} + \coth^{-1}\sqrt{\frac{\rho_n}{\rho_{n-1}}})\right)\right)\right]\right\}\right\rangle \tag{7}$$

$$k_n = \frac{1+i}{\delta_n} \tag{8}$$

$$\delta_n = \sqrt{\frac{2}{\sigma_n \mu \omega}} \tag{9}$$

δ_n is the usual skin depth of the n-th layer. Notice the R_n depends only on the parameters describing the electric section, including the ratio between the skin depth and the thickness of each layer. Moreover R_n is not a function of the primary field. For a plane wave H_y is a function of the source strength only. Thus

$$Z = E_x/H_y = Z_1 R_n \tag{10}$$

is independent of the strength of the primary field and thus changes in the source strength and the propagation conditions do not affect the function $Z_1\ R_n$ which carries the information about the electric structure of the medium as a function of the frequency.

Returning to eq. (6) we note that the ratio of ρ_T/ρ_1 as a function of frequency shows the degree to which the impedance measured at a surface point differs from that of a uniform half-space with a resistivity ρ_1. The ratio ρ_T/ρ_1 is a function of the parameters of the medium and the frequency ω. The frequency spectrum of ρ_T/ρ_1 combined with the spectrum of the phase shift between E_x and H_y measured at various spatial locations provides the data which after inversion will provide the appropriate underground image.

Before closing this section we should note one more item which is equally valid for a horizontally layered or a uniform medium. According to our assumptions about the source of the primary magnetic field, the primary magnetic field H_y^{o} does not depend on z. As $z \rightarrow \infty$, H_y^{o} remains the same. However the total field $H_y^{o} + H_y^{s}$, where H_y^{s} is the secondary field, should approach zero for $z \gg \delta$. Hence $H_y^{s} = -H_y^{o}$. It is then easy to show using Ampere's law that

$$H_y\,(0) = H_y^{o} + H_y^{s}\,(0) = 2\,H_y^{o} \tag{11}$$

The magnetic field at the surface is greater than the primary, by a factor of 2, independently of the profile $\sigma(z)$ of the conductivity. We can thus draw several conclusions valid for horizontally stratified media and plane wave incidence. The value of $H_y(0)$, does not depend on the conductivity profile. Thus, only the horizontal component of the electric field, $E_x(0)$ contains information about the electrical properties on the medium. This implies that in measuring the impedance Z, we are in fact measuring the electric field multiplied by a constant

$$Z = (1\,/\,2H_y^{o})\,E_x(0) \tag{12}$$

This constant $1\,/\,2H_y^{o}$, allows us to normalize the measurements, by removing the influence of the intensity of the primary field.

2.2 Ionospheric Sources

Following Cagniard's work and given the remarkable simplicity of the MT concepts, a major effort in em geophysical exploration has been in developing artificial or finding natural sources that approximate the properties of the plane wave upon which the MT theory is based.[9] One direction was to use the natural noise field, generated by lightning or by natural currents flowing in the ionosphere.[1,9] The technique has been shown to be quite successful in approximating a plane wave under some conditions. It has, however, serious drawbacks due to the randomness of the currents, lack of energy in important frequency bands, and strong seasonal and latitudinal variations. The alternative was the development of artificial sources. Again such sources have produced often important results especially for high frequencies, but have severe drawbacks as to the validity of the plane wave and impedance concepts. The problems with artificial sources and the restricted validity of the plane wave and impedance are discussed in Zonge (1989) and Wanamaker (1997).

The development of ionospheric sources (IS) may create as close to an ideal plane wave, satisfying the Tikhonov-Cagniard conditions, as possible. The em waves produced by these sources couple to the TEM mode of the earth ionosphere waveguide. The primary field away from the source is composed only of a vertical magnetic field E_z°, H_x°. The surface magnetic field $H_y(0) = 2H_x^{\circ}$, as discussed above, while the value of $E_x(0)$ depends only on the ground conductivity within a skin depth at the relevant frequency. Since the free space wavelength is large and the attenuation in the waveguide very low, of the order of 1 dB/Mm, a very uniform primary H_y° is present.

A drawback of the impedance concept based on simultaneous measurements of $E_x(0)$ and $H_y(0)$, especially for covert operations or operations where use of low flying airborne sensor platforms is desirable, is the need for measuring the horizontal electric field. Measurements of such electric fields require good contact with the ground thus preventing purely airborne sensors and making covert operations cumbersome. The possibility for using only magnetic measurements, using sensitive gradiometers or observing more than one closely located site, while maintaining the concept of

impedance for the inversion process will greatly enhance the practical applications of MT techniques, since the measurements will not require contact with the ground.

2.3 Alternative Impedance Definitions

In the above discussion, the complex impedance values used in the inversion algorithms required measurements of both the electric and magnetic fields. However, it can be shown following similar procedures to the Tikhonov-Cagniard analysis [e.g. see Kaufman and Teller, 1981, p. 146-155], that for a plane wave and horizontally stratified medium there are two alternative definitions of the impedance, which permit the computation of its spectrum using measurements of only the vector magnetic field H and/or its derivatives. The first definition is[9]

$$Z = i\omega\mu_0 \,[H_z/(\partial H_z/\partial_z)] = i\omega\mu_0 \,[(1/(\partial/\partial_n)\vartheta n H_z)] \qquad (13a)$$

Or using the fact that $\nabla \cdot \mathbf{H} = 0$

$$Z = -\omega\mu[H_z/(\partial H_x/\partial_x) + (\partial H_y/\partial_y)] \qquad (13b)$$

As a result observations using horizontal or vertical magnetic gradiometers, or simultaneous observations in two or three closely located sites would, in principle, give the complex impedance required as input to the inversion code. This can be accomplished without the need for physical contact with the ground, possible from low flying airborne platforms

The second definition, involves what is traditionally called a tipper (Kaufman and Teller, 1981). It is given by

$$Z = A\omega\mu_0 \,(H_z/ H_x) \qquad (14)$$

Where A is a constant. This again permits the determination of the impedance spectrum required in the inversion algorithms. The scalar definitions of the complex impedance can be generalized in a straightforward fashion to their tensor equivalents (Vozoff, 1989; Spies and Frishknecht, 1989).

Applicability of the impedance derivation using the tipper (equation 14), or the equivalent impedance derived using equation 13 need to be investigated. Excellent comparisons can be performed using the generalized 3-D code developed by us. We thus model the E,H, and dH/dX components using the 3-D code and under different conditions. We next compare the Z values derived using equations 12,13, and 14. These comparisons will validate the Tikhonov approximations and their applicability under different situations. This will allow us to define appropriate detection and inversion strategies.

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